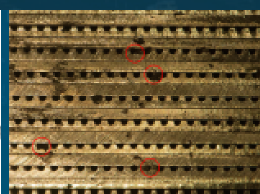
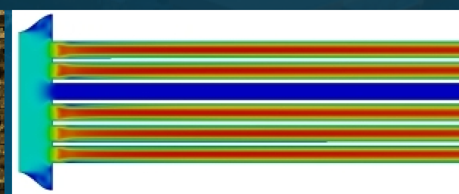
SAND2022-5025C

Sandia National Laboratories

sCO_2 Heat Exchanger Performance and Fouling Effects





PRESENTED BY

James J. Pasch

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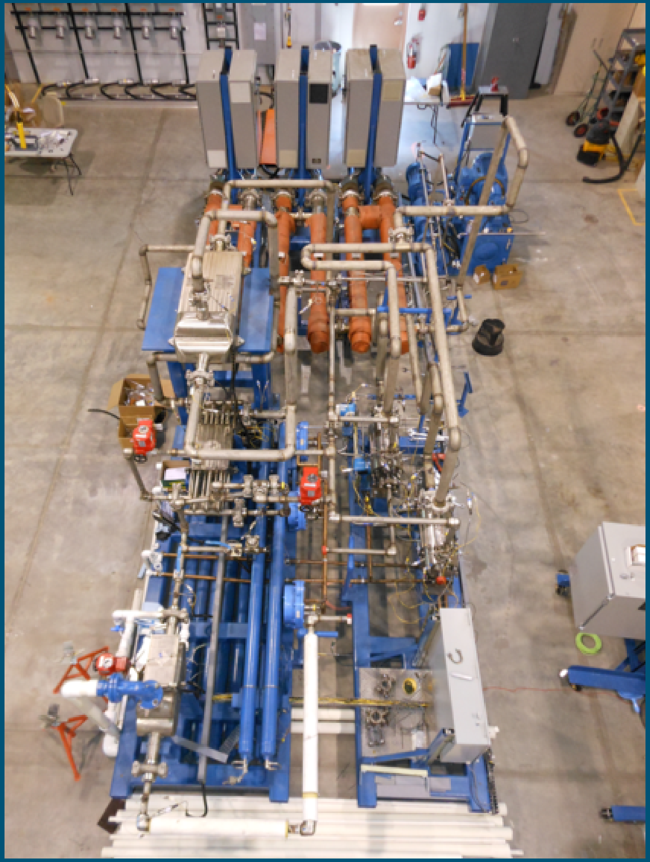
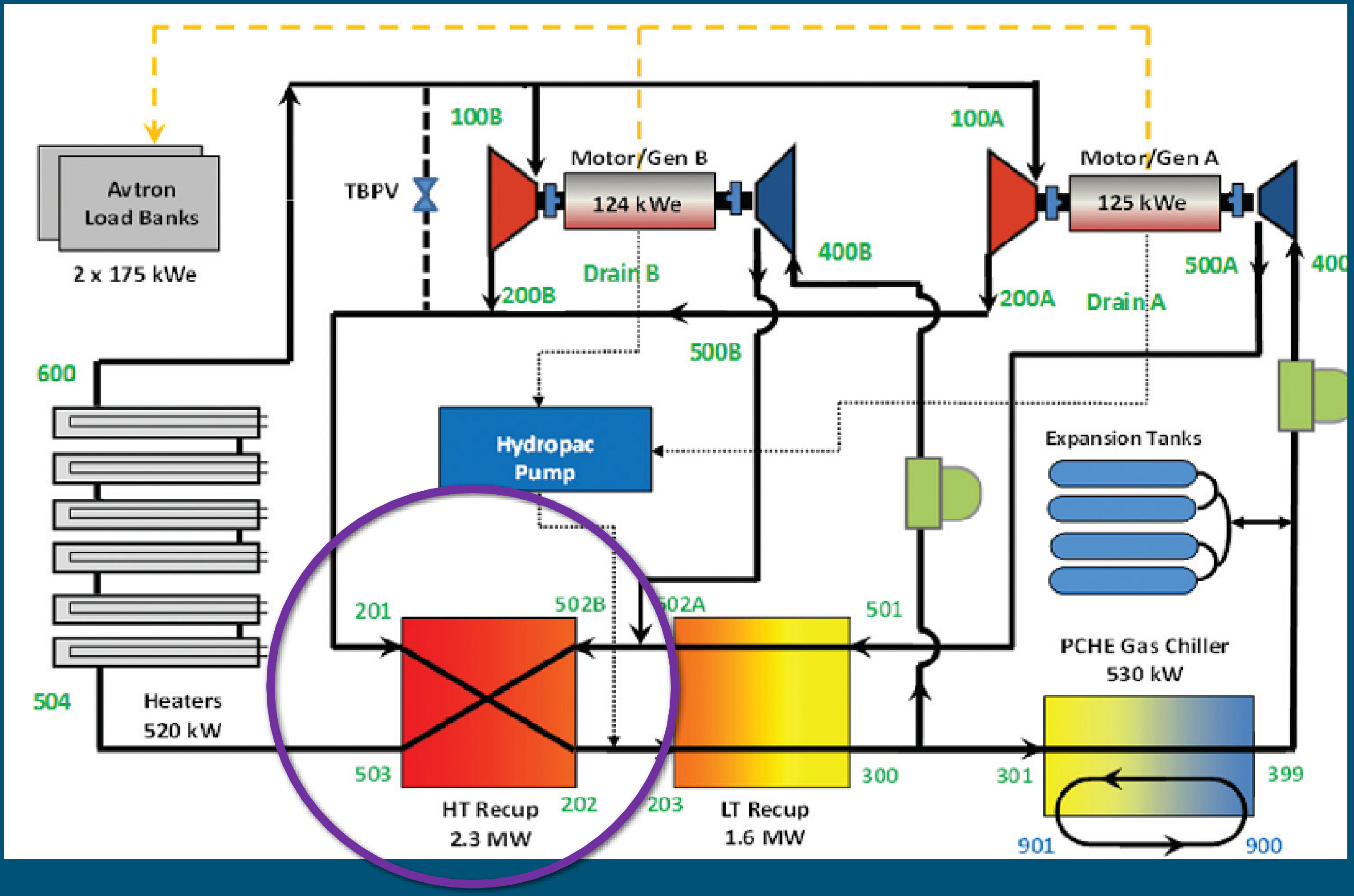
Background – Our Work

- Sandia National Laboratories (SNL), Nuclear Energy Systems Laboratory (NESL) / Brayton Lab in Albuquerque, NM, USA.
- Primary objective is to develop a new type of power system, the closed Brayton cycle using carbon dioxide, for small modular reactors
- Type of work we do
  - Turbomachinery and component R&D
  - Heat exchanger R&D
  - System design, operation, and performance assessment and predictions
- Primary customer is DOE-NE
- Unique feature of this power cycle is that it is heat source agnostic → any heat source works.



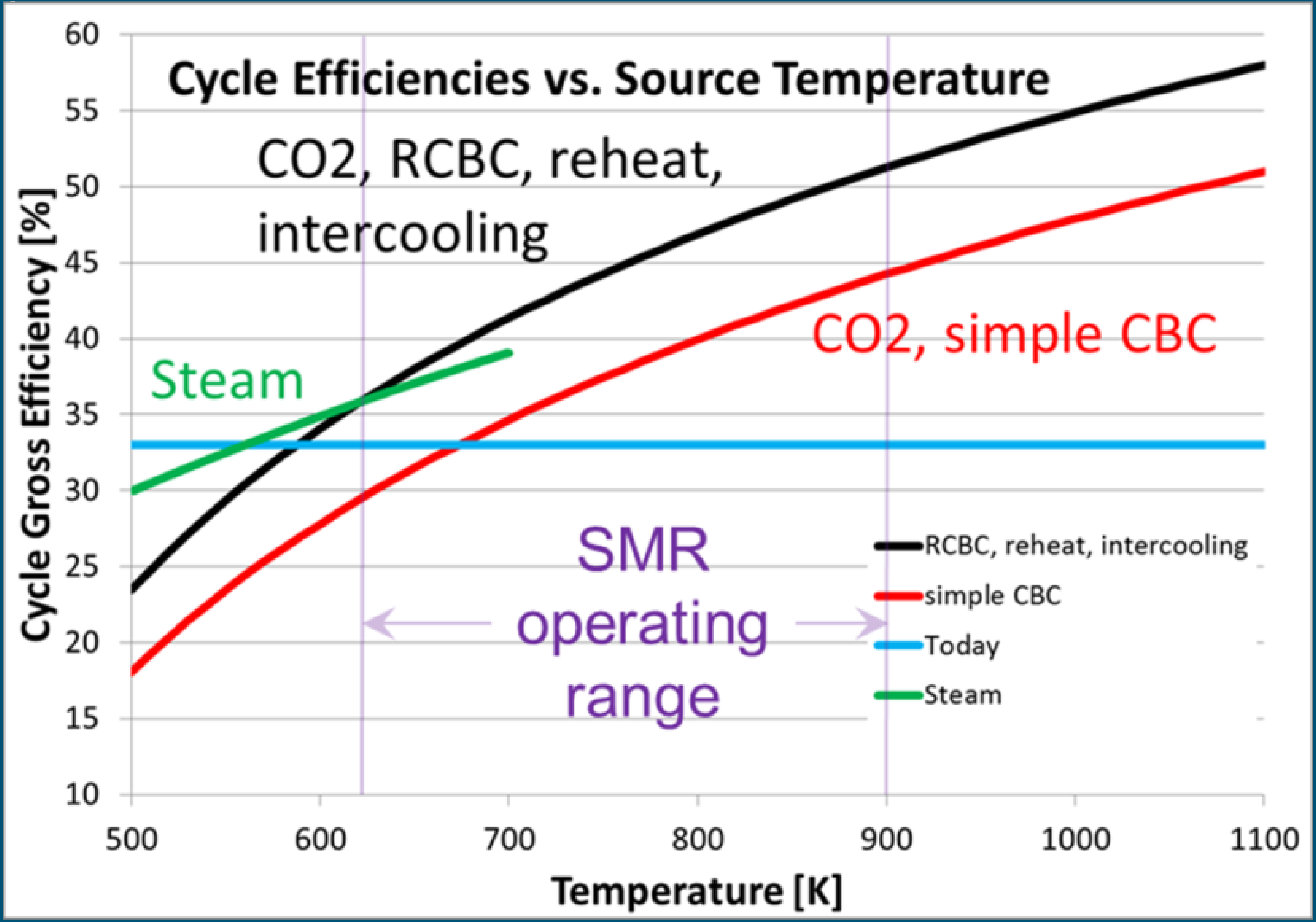
SCO_2 RCBC DEVELOPMENT PLATFORM

1. No constant temperature heat rejection → greater heat recuperation
2. Gas compression near critical point → less compressor work
3. Improved matching of thermal capacitance flows in LTR



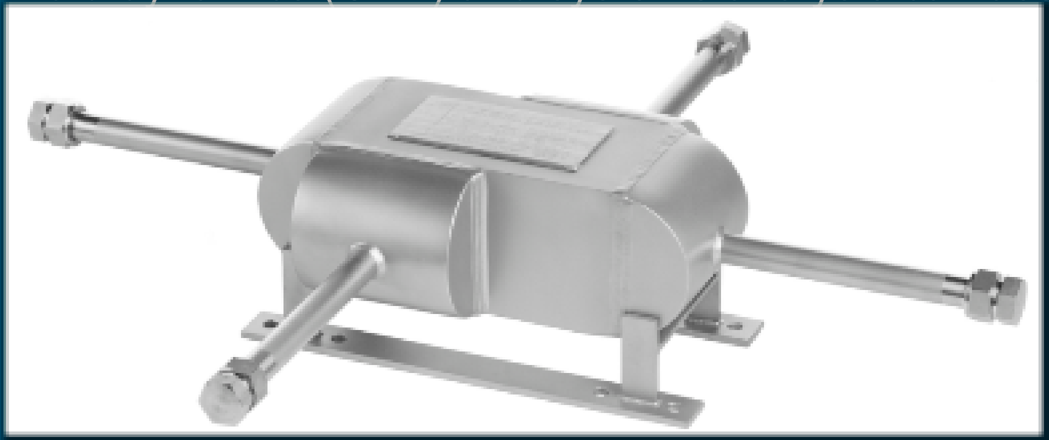
The Thermodynamics of the RCBC

- The theoretical performance of the sCO2 power cycle has generated excitement and investment.
- Higher temperatures give higher efficiency. So materials is a crucial factor.



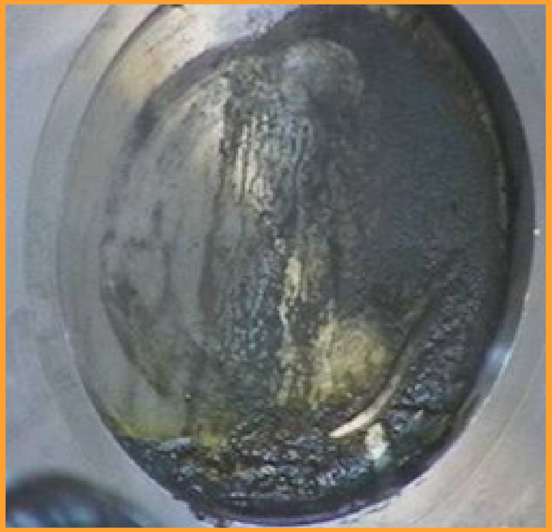
Heat Exchangers – a Critical Component

- Compact heat exchangers are a critical component to the SNL sCO_2 Brayton recompression closed Brayton cycle (RCBC)
- 2-3 MW thermal heat transfer in a recuperator core with 0.18 m^3 volume – extremely high power density
- This is achieved by very large heat transfer surface area and very small flow channels.
- Fouling has potential to reduce heat exchanger efficiency and overall performance
- Computational fluid dynamics (CFD) and systems analysis can assess fouling impact

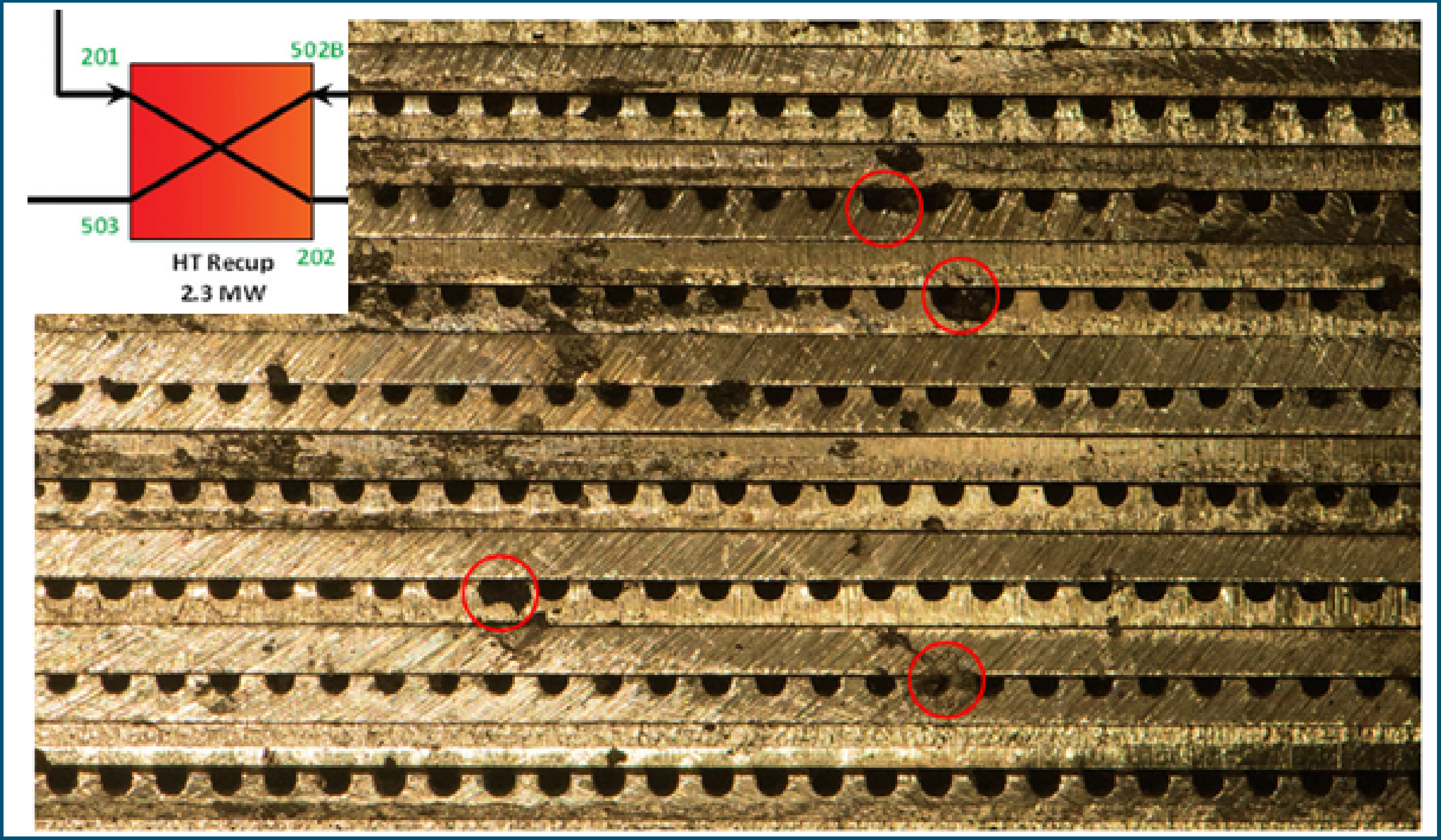


FOULING CAUSES, ISSUES, AND MITIGATION

- Small channels, complex passages mean more potential for fouling
- Fouling types: precipitation, particulate, chemical, corrosion, solidification
- For gas-like flows, performance degradation observed via pressure drop
- Sealed compact HX not recommended for high fouling applications
- Both physical and chemical cleaning methods available

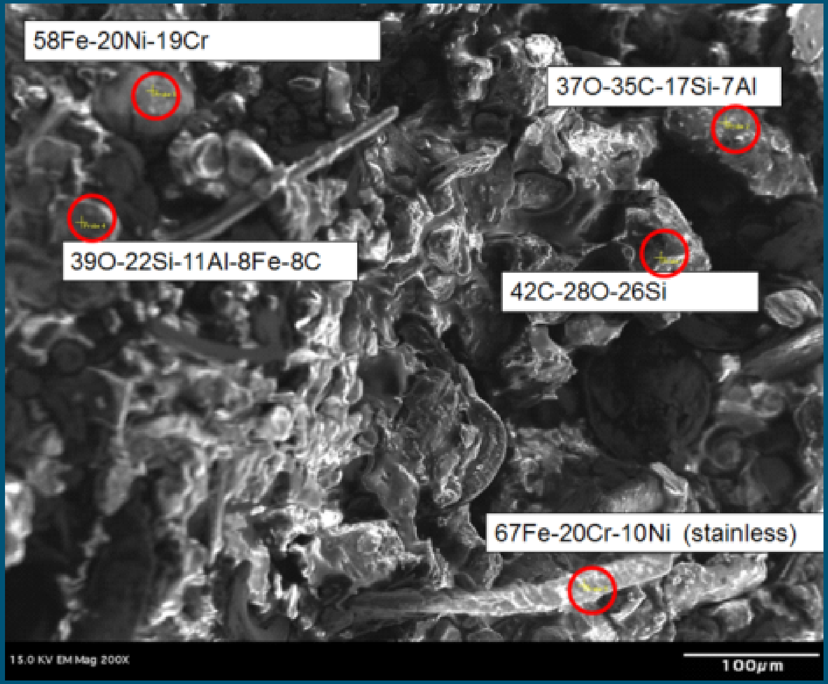


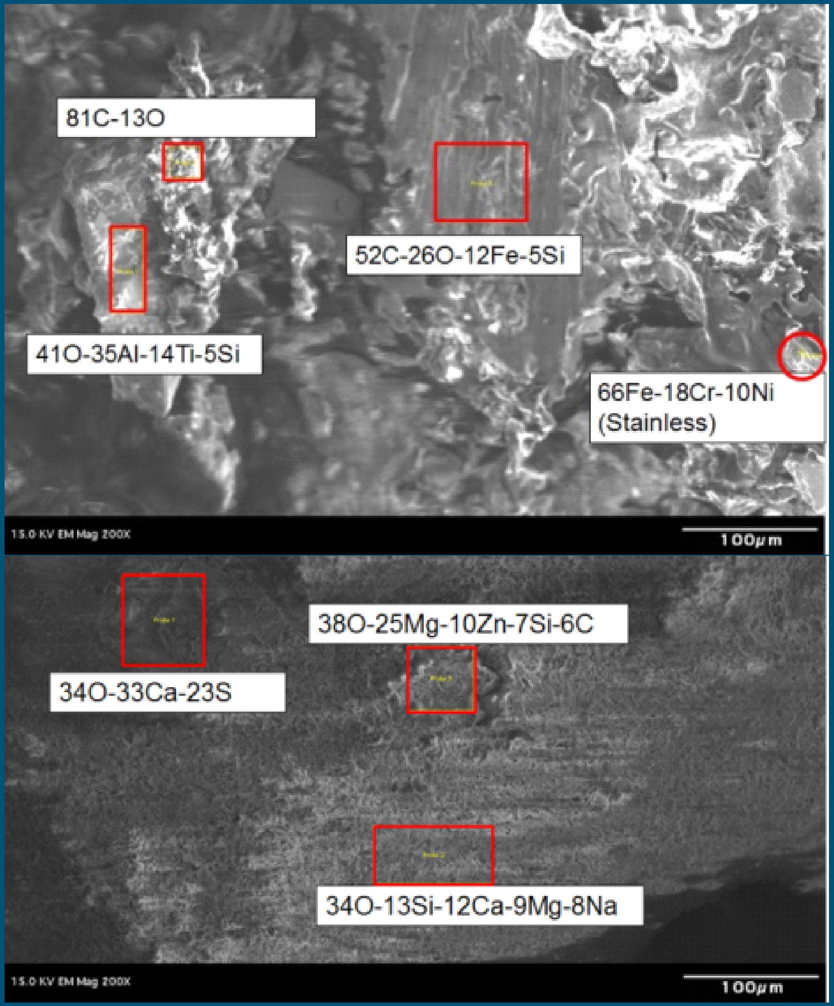
FOULANT BUILDUP IN HIGH TEMPERATURE RECUPERATOR (HTR)



ENERGY DISPERSIVE X-RAY SPECTROSCOPY (EDS) ANALYSIS OF FOULANT

- Metallic, inorganic, and organic compounds present
- Source is piping metals, graphite, and soil contamination





Analyses of Fouling Effects – Trade Studies

- Supercritical carbon dioxide is an excellent solvent. Assume fouling agent
  - is entrained at high pressure, high temperature portion of loop
  - precipitates out within the high temperature recuperator (HTR) on the low pressure side as the fluid cools → flow stream discharged from the turbine
- Pressure loss is increased on only the low pressure side of the HTR due to increased flow resistance.
- Heat transfer is diminished between the two flow streams due to increased heat flow resistance.
- While the assumption for the studies specifies precipitate fouling, the analysis mimics the effects of large scale fowling of any of the 5 types on the HTR low pressure leg.
  - Precipitation
  - Particulate
  - Chemical
  - Corrosion
  - Solidification

Trade Study Analyses

- A Fortran program, RETS©, has been developed that predicts component and system performance analysis given 12 user inputs.
- The program facilitates trade study analyses.
- Yellow table below shows nominal values for the following trade studies
- There are two primary consequences of fouling
  - Increased pressure loss, simulated by varying the HTR low pressure leg pressure loss.
  - Decreased heat transfer effectiveness, simulated by varying the HTR effectiveness

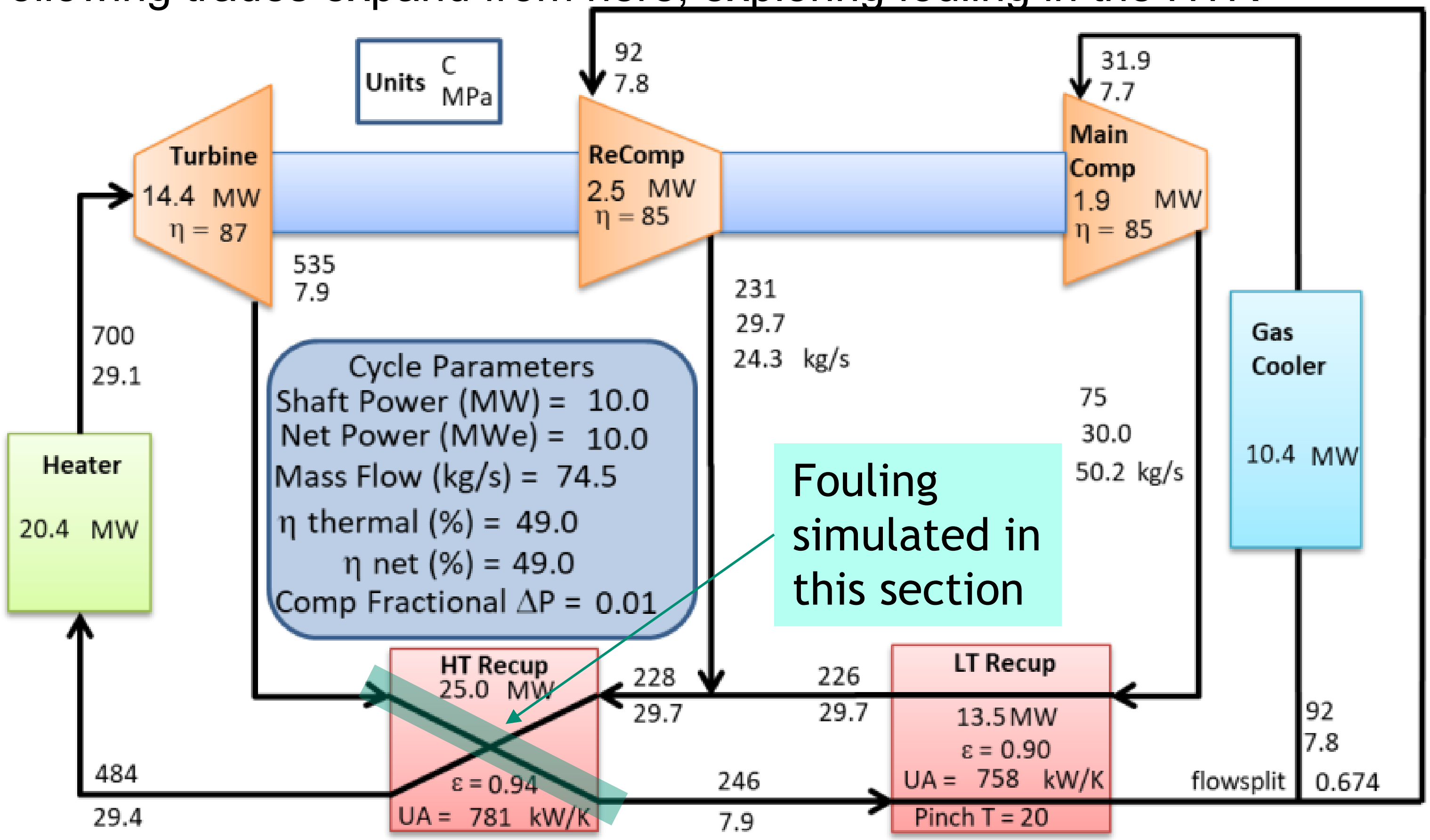
Parameter	Units	Value
Main compressor inlet temperature	°C	31.85
Main compressor inlet pressure	MPa	7.7
Compressor discharge pressure	MPa	30
Turbine inlet temperature	°C	700
HTR Effectiveness	-	Variable
LTR Effectiveness	-	0.9
LTR pinch temperature	°C	20
Turbine efficiency	%	87
Main compressor efficiency	%	85
Recompressor efficiency	%	85
Fractional pressure drop through each major compon	ΔP/P	Variable
Electric Power Output	MWe	10

$$\varepsilon = \frac{T_{in,hot} - T_{out,hot}}{T_{in,hot} - T_{in,cold}}$$

0.01 for all components except HTR low pressure side

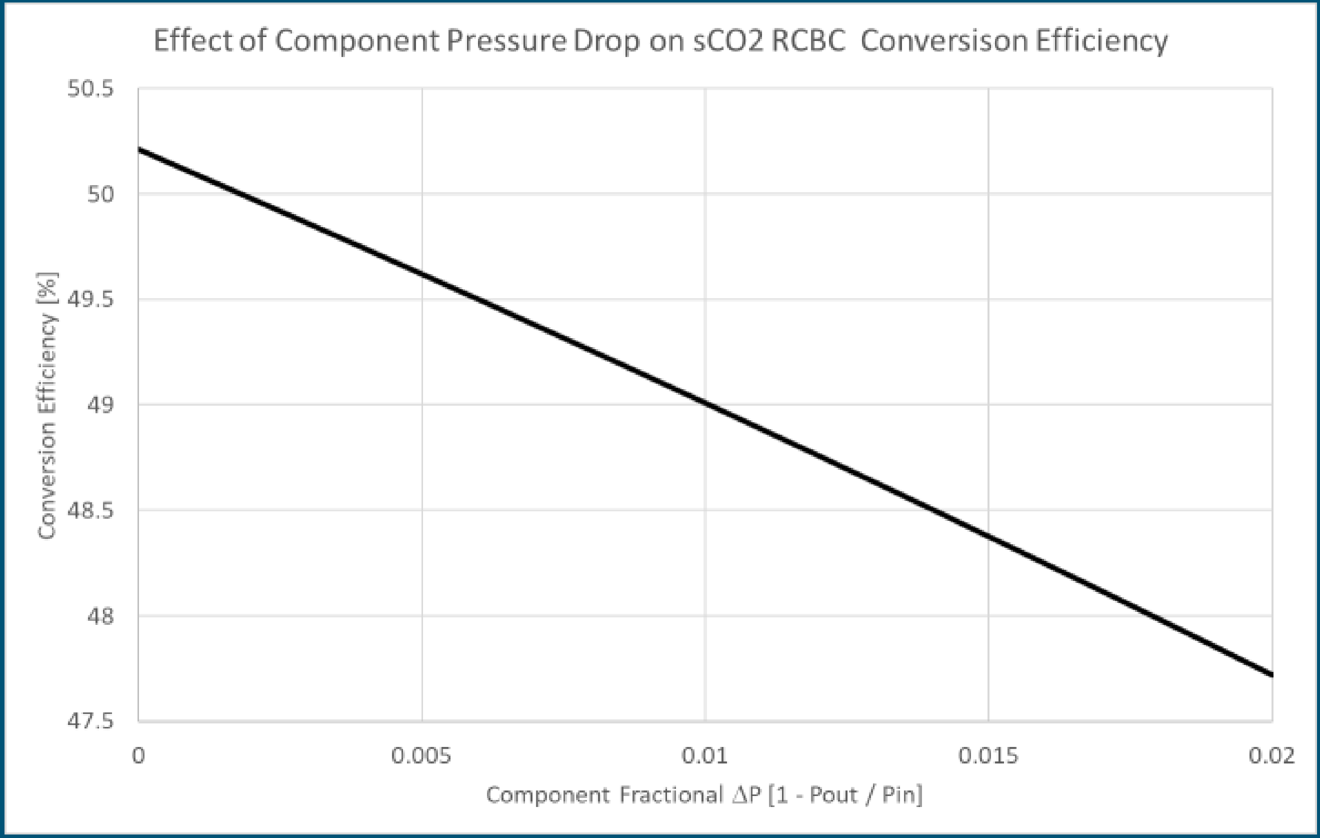
Flow Sheet for Nominal Parameter Values

- This represents a realistic operational target for a 10 MWe power conversion system.
- Following trades expand from here, exploring fouling in the HTR



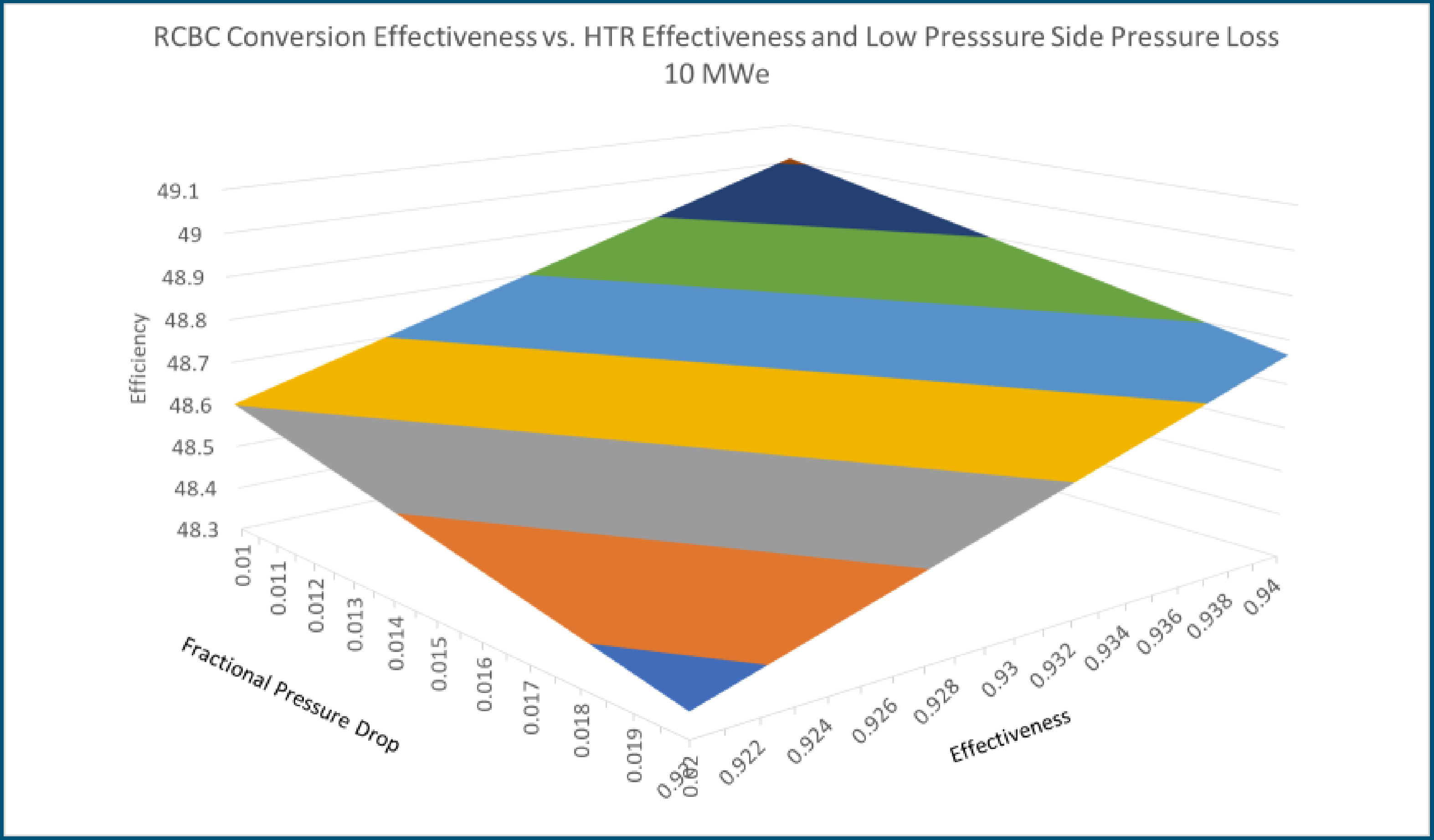
Effect of Pressure Loss on RCBC Efficiency

- Pressure ratio for typical sCO_2 RCBC is on the order of 3 – very low compared to steam cycles that are > 1000.
- Therefore, the cycle efficiency is very sensitive to pressure losses
- Given that extensive recuperation is the purpose of elevating the system pressure from a Rankine cycle to the supercritical region of a Brayton cycle, any degradation in recuperation is significant.



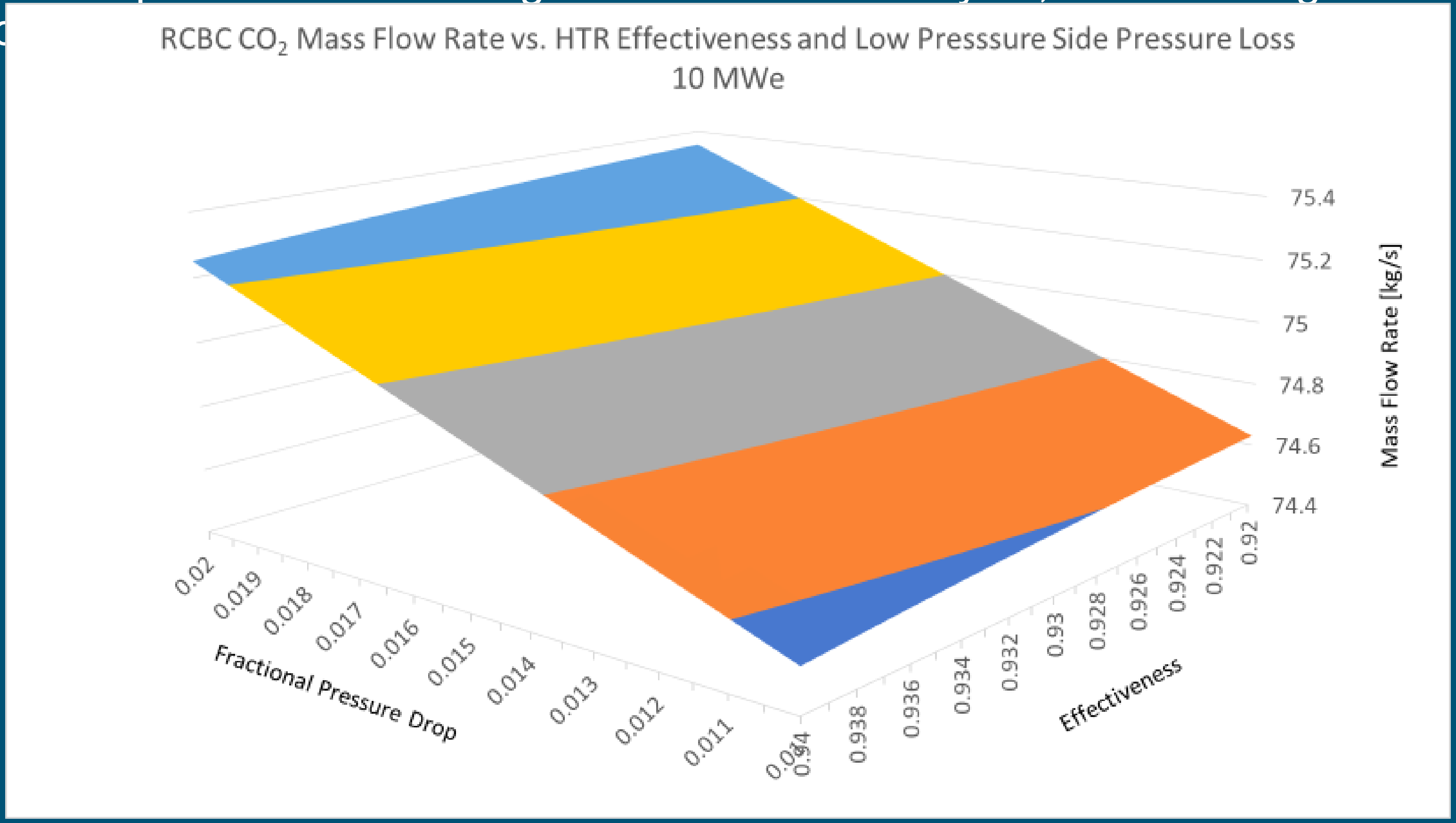
Fouling: Trade Effect on Cycle Efficiency

- Conversion efficiency is adversely affected by both increased pressure loss and decreased effectiveness



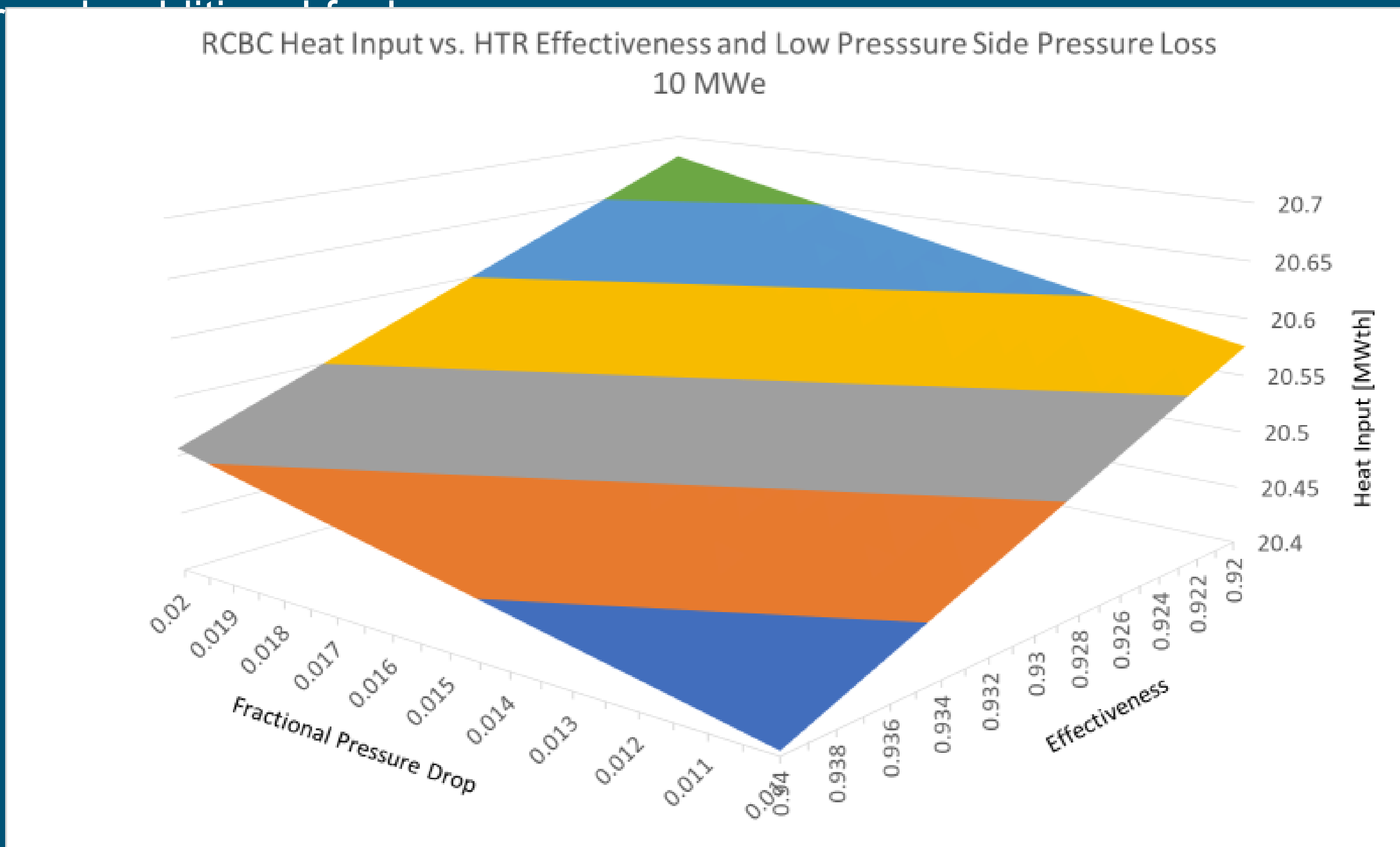
Fouling: Trade Effect on Mass Flow Rate

- CO2 mass flow rate to maintain 10 MWe of electrical output increases with pressure loss and is nearly independent of HTR effectiveness changes.
- Increased mass flow rate will increase wear on components and also increase pressure loss throughout the rest of the cycle, exacerbating the pro



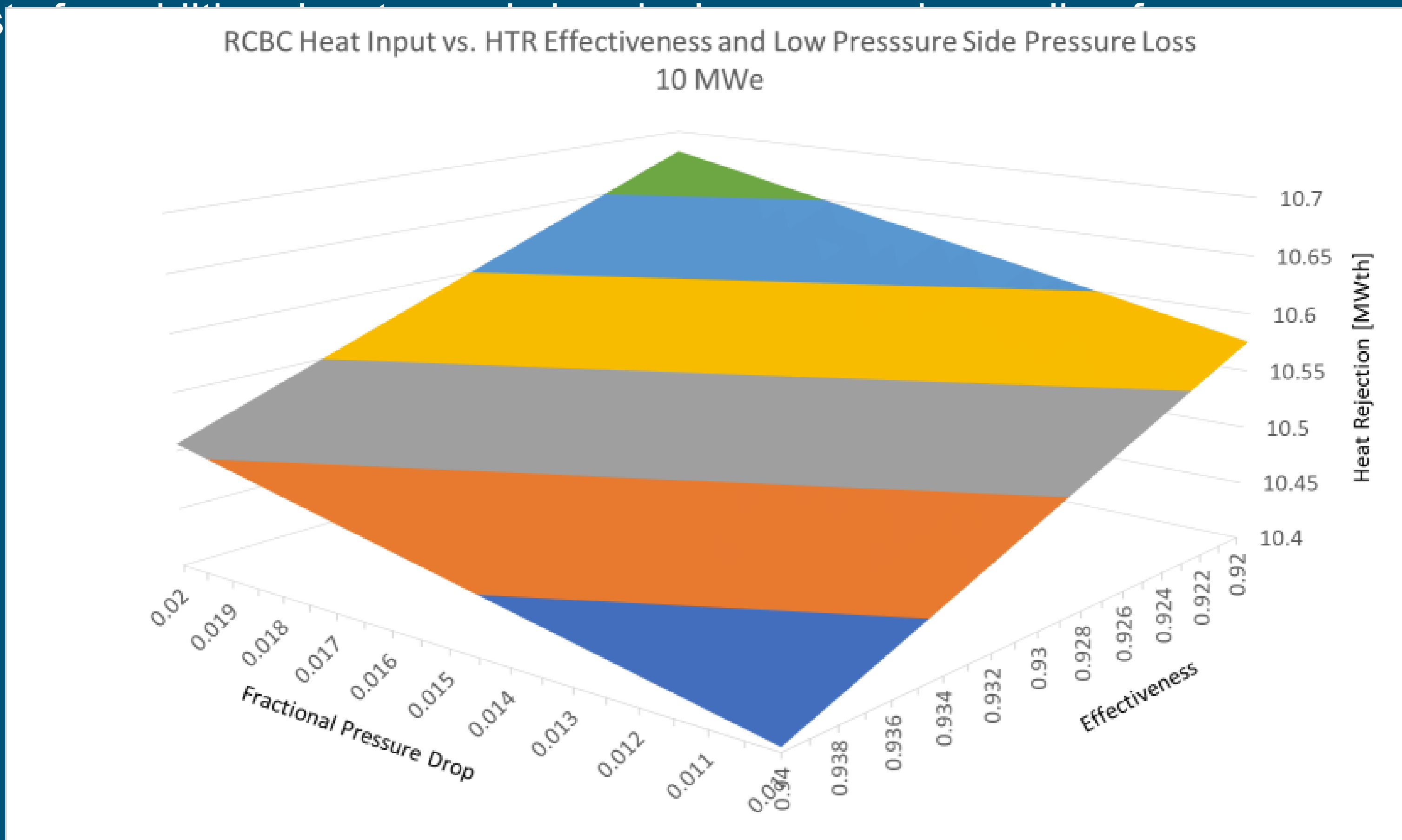
Fouling: Trade Effect on Heat Input

- Thermal heat input to cycle to maintain 10 MWe of electrical output increases with increasing pressure loss and decreasing HTR effectiveness.
- This increases wear on heat source and increases operating costs thr



Fouling: Trade Effect on Heat Rejection

- Thermal heat rejection from cycle to maintain 10 MWe of electrical output increases with increasing pressure loss and decreasing HTR effectiveness.
- This increases wear on heat rejection system and increases operating cos



CFD MODEL OF PCHE CHANNEL PLUGGING

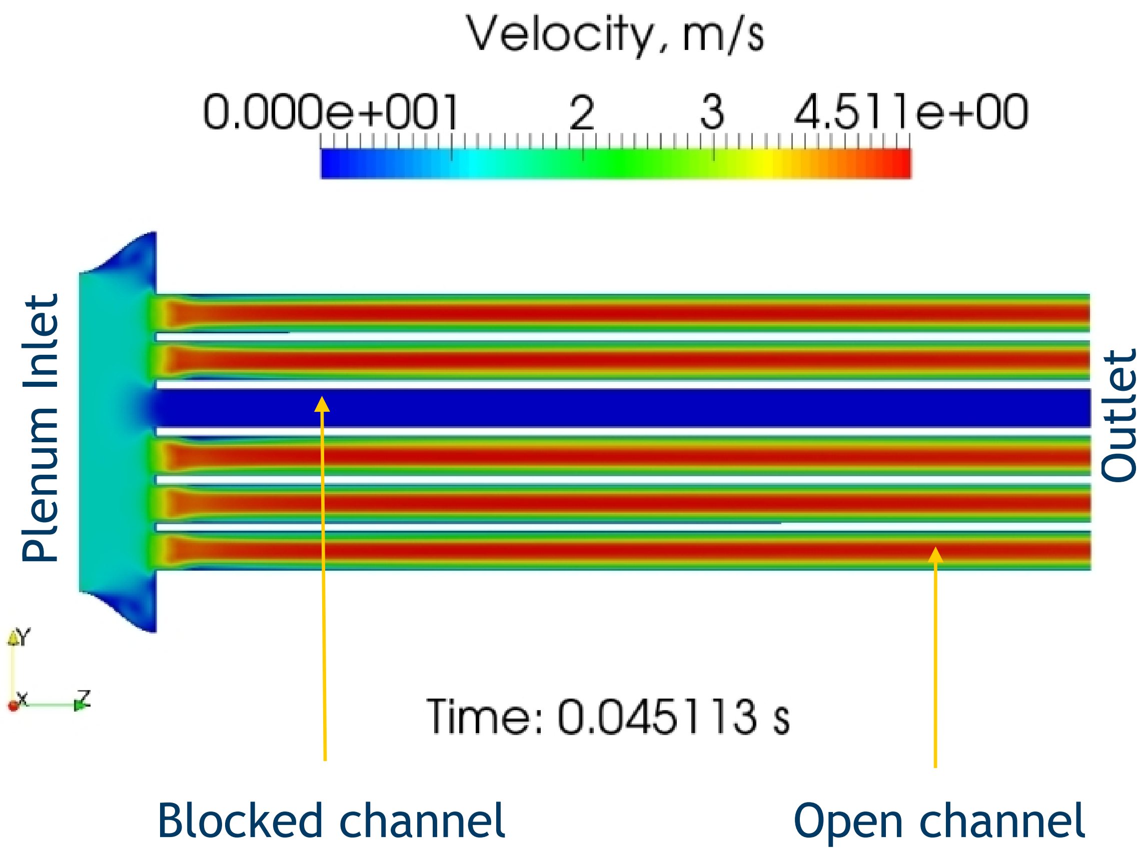
Conditions

- SNL Fuego code[1]
- Channel array size n^2, n = 2, 3,…,9 modeled with either all open or one blocked (fouled) channel
- 5.9 kg/s sCO_2 at 7.92 MPa
- Re = 8.93×10^3 (moderately turbulent)
- D_H = 0.959 mm

Assumptions

- Mass flow rate at inlet manifold normalized for identical, fully-developed flow, irrespective of array size
- Manifold dimensions normalized using D_H
- Open boundary condition at exit

Cross-section of 6x6 channel array with one fouled channel:

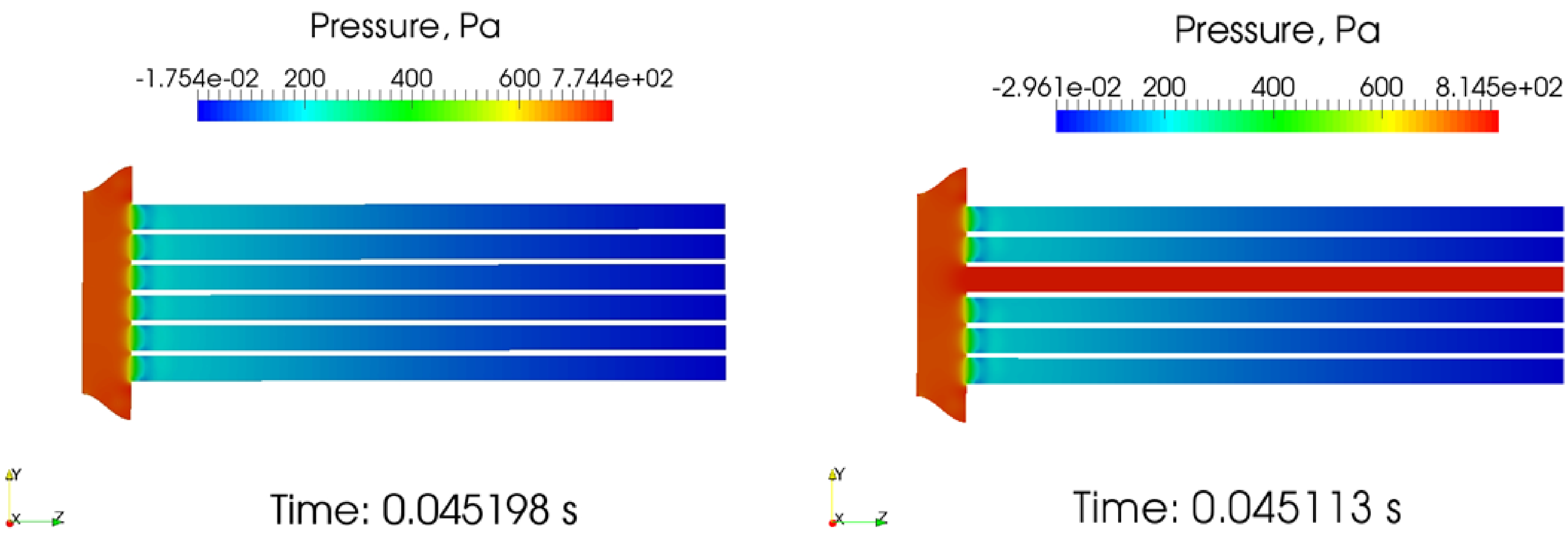


1. S. Rodriguez, Swirling Jets for the Mitigation of Hot Spots and Thermal Stratification in the VHTR Lower Plenum, Ph.D. dissertation, University of New Mexico, 2011

CFD MODEL FIDELITY AND VALIDATION

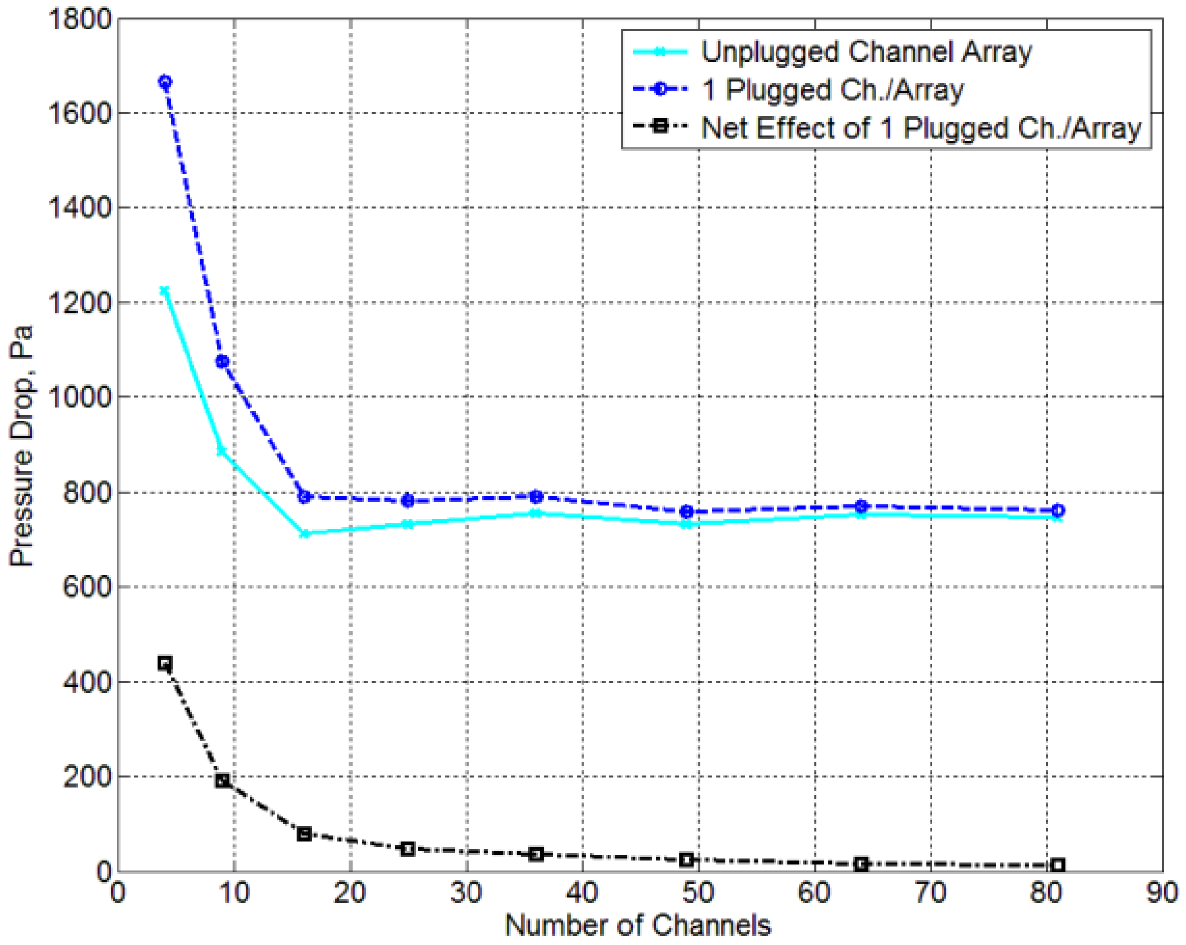
- Performed mesh spatial convergence: medium, fine, and very fine meshes
- Used radial biasing, with first computational node near wall at y+ = 1
- Used good mesh metrics (e.g., aspect ratio, skew, condition number)
- Used the dynamic Smagorinsky large eddy simulation (LES) turbulence model
  - Suitable for low to high Re with swirl, as is the case with the PCHE
- LES results compared favorably with other suitable turbulence models [e.g., 2006 k-Ω and direct numerical simulation (DNS)]
- Confirmed that mesh elements were in the range of the Taylor and integral eddies for the LES calculations, and in the Kolmogorov eddies for the DNS calculations

PRESSURE DROP IN 6X6 CHANNEL ARRAY



(L) All open channels, (R) one plugged channel

PRESSURE DROP WITH INCREASING # CHANNELS



SUMMARY

- Small fraction of plugged channels will not appreciably impact HX effectiveness or pressure loss
- Whereas channel diameter is small, large number of channels mitigates concern for localized fouling caused by small number of particulates.
- Large scale, or homogeneous fouling, as would be expected with precipitate, solidification, or corrosion fouling, is shown to have potentially significant effects.
- Increased pressure loss at HTR (or any component) adversely affects components throughout the cycle by requiring more mass flow to maintain powered.
- Fouling that degrades heat transfer can have a noticeable impact on system performance and increases load requirements for heat input and rejection.
- Compact HX are suitable for sCO_2 RCBC use, but common precautions are warranted.